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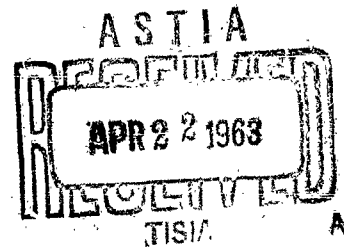
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XENON FLASHTUBES AS SOURCES OF THERMAL RADIATION

by
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ADMINISTRATIVE INFORMATION

This report covers a facet of the work authorized during FY 1961 and 1962 by the Defense Atomic Support Agency (NWER Program A8a, Subtask 12.006). Details of this work are found in the U. S. Naval Radiological Defense Laboratory FY 62 Technical Program as Program A6, Problem 4, entitled "Ignition and Fire Propagation by Thermal Radiation," the objective of which is to provide a scientific basis for controlling the incendiary effects of nuclear detonations by investigating the thermochemistry of ignition and combustion for cellulosic solids exposed to intense thermal radiation. Funds for this work during FY 62 were furnished by the Defense Atomic Support Agency on MPR 501-62.

ACKNOWLEDGMENT

Appreciation is extended to Mr. C. P. Butler for his contributions to this work among which are included the construction of the calorimeter elements with attendant thermocouples and platinum-black coatings.

Further acknowledgment is due Mr. J.R. Nichols whose punctilious design and construction of most of the experimental equipment has resulted in many hours of trouble-free operation.

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ABSTRACT

Thermal radiative properties of xenon flashtubes have been studied by measuring radiant energies per flash and peak irradiances incident on small objects located at the center of selected helical flashtubes. Methods are described for determining these properties by employing black-body calorimeters in conjunction with oscillographic presentation of intensity vs. time. Thermal pulses were found to be quite reproducible and are of the order of 1.0 to 1.7 cal/cm² per thousand joules of electrical input energy depending on the type of flashtube. Peak irradiances of over 7,000 cal·cm⁻²sec⁻¹ were observed, and the influence of varying the capacitance and voltage was also determined.

In addition, some electrical characteristics of the flashtubes, such as current and resistance were included in the measurements.

SUMMARY

The Problem

With the innovation of xenon flashtubes as sources of thermal radiation for the continuing experimental studies on ignition of cellulosic materials, it has been necessary to determine quantitatively the total energies and peak irradiances to which the exposed samples are subjected under varying combinations of flashtube circuit capacitance and voltage.

The Findings

Within the rated values of the flashtubes, the radiant energy per flash was found to be directly proportional to the electrical energy dissipated in the discharge regardless of the particular combination of capacitance and voltage. On the other hand, the peak irradiance varies linearly with the voltage squared and only slightly increases with capacitance. Also established has been the influence of these parameters on pulse shape and (to a more limited extent) on the spectral distribution of the radiant energy.

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INTRODUCTION

BACKGROUND

Continuation of studies in this Laboratory on the flash pyrolysis of cellulosic materials has led to the requirement for a thermal source which will heat samples uniformly and rapidly (in less than a second) to high temperatures. Because the carbon-arc sources which have been used extensively in the ignition program fall short of this requirement, other possible sources were considered. The feasibility of dielectric heating of cellulose at microwave frequencies was first studied, and the report¹ indicates that this technique does have possibilities as a useful method for heating cellulosic materials. However, subsequent attention to dielectric heating, which requires complex and expensive equipment, was held in abeyance in view of the outstanding success reported by Nelson, Lundberg, and Kuebler²⁻⁶ at Bell Telephone Laboratories who used the illumination from capacitor discharges through flashtubes to instantaneously heat a variety of materials.

Preliminary experimentation in this Laboratory to determine the applicability of the flash method to ignition studies consisted of placing thin strips of blackened cellulose within the helix of a high-energy xenon flashtube so that both surfaces of the sample were irradiated, thus improving the uniformity of the temperature profile. It was found that a single discharge of a thousand joules will completely decompose such a sample in a fraction of a millisecond. The reaction is so violent that an explosion results which sounds like a gun shot.

This provided quick and dramatic justification for immediately commencing the equipment construction and flashtube evaluation reported herein.

Of course, one necessary condition for efficient use of such a thermal source is that the absorptance of the material to be heated must be reasonably high in the visible and near infrared, because most of the radiant output from the xenon discharge is in that part of the spectrum. Inasmuch as most cellulosic materials are white, extensive earlier work in this Laboratory has shown that the inclusion of approximately 2% carbon black within the bulk of cellulose sheets has rendered them an absorptance close to 100% over this region of the spectrum.

PREVIOUS FLASHTUBE STUDIES

Over the past couple of decades, flashtubes, particularly those containing xenon as the discharge gas, have become prominent as illumination sources for photography. This work was pioneered by Edgerton⁸⁻¹² and a number of others^{13-20,33} who have published papers on the electrical characteristics and light output of flashtubes. Within the last decade several investigators²¹⁻²⁴ have applied various types of flashtubes to photochemical studies to provide a source of radiation in the near ultraviolet. Except for the work at Bell Laboratories and a series of detonation experiments carried out by Berchtold and Eggert,^{25,26} there is no record of flashtubes being employed as thermal sources, and until recently, the literature was nearly devoid of information pertaining to their thermal radiative properties.*

*Prior to the completion of this project, results of some thermal measurements on flashtubes were published by Kuebler and Nelson.²⁷

OBJECTIVES

The investigations described here were directed toward providing the following information about flashtubes pertinent to their utilization in the ignition program of this Laboratory:

- (1) Establish quantitative relationships between radiant energy per flash and electrical input energy.
- (2) Determine peak irradiances available and the factors which control them.
- (3) Develop a method for obtaining the above values.
- (4) Ascertain the dependence of thermal pulse shapes on electrical parameters.
- (5) Determine some of the electrical characteristics.
- (6) Gain at least some limited information on spectral distribution.
- (7) Estimate temperatures attainable in samples.

EQUIPMENT and TECHNIQUES

PYROLYZING UNIT

A convenient arrangement for flash pyrolyzing a sample of solid material and subsequently analyzing the pyrolysis products is achieved by placing an open helical flashtube coaxially around a segment of glass or quartz tubing which contains the sample. The tubing plus sample can then be incorporated into a gas chromatography unit by connecting it in series with the helium inlet stream. With this arrangement, the volatile products are immediately swept into the chromatography column when the flashtube is discharged. A similar arrangement is used to pyrolyze solid samples in a mass spectrometer.

Here, the sample is contained in the closed-off end of a segment of glass tubing which opens into the ion source, and the gaseous products have only a few inches (a small fraction of the mean-free-path) to travel before encountering the ionizing electron beam.

With these two applications as objectives, the necessary features were incorporated into the design of the compact pyrolyzing unit shown in Fig. 1. The quartz sleeve (not shown) centered inside of the flashtube helix plus the teflon plates on each end are removable. When in place, they provide an annular space through which hot air can be circulated outside of the sample-containing tube to prevent condensation of volatile products inside of it. This also protects the flashtube in case of failure of the sample tube. Aluminum foil is wrapped externally around the flashtube to serve as a reflector and as the trigger electrode to initiate the discharge. The trigger transformer which produces a sharp 15 KV pulse is located inside of the housing between the legs of the flashtube; the housing itself was constructed of transite and can be mounted in any position. The unit is connected to the capacitor bank and triggering circuit by coaxial cables to minimize extraneous electrical radiation.

CHOICE OF FLASHTUBES

Xenon flashtubes have been used exclusively in this work for the following reasons: (1) the significantly greater luminous efficiency of capacitor discharges through xenon,¹⁸ (2) the spectral distribution of their illumination is similar to that of sunlight as well as nuclear weapons, (3) numerous sizes and configurations are available commercially. The requirements of this project for an open helical configuration and high energy capability sharply narrowed the choice, and for this work most of the measurements were made on the General Electric FT-625. This is a factory modification of the FT-623, a



Fig. 1. The pyrolyzing unit with an FT-625 positioned externally for illustration. Above the flashtube is the vacuum calorimeter which includes the blackened silver cylinder suspended by the thermocouple wires.

five-turn 5.5-cm diameter helix wound from 12-mm o.d. quartz tubing. The two are electrically identical,²⁸ and the only difference is one of configuration wherein the FT-625 is not mounted on a base and the legs are perpendicular to the axis of the helix rather than parallel. The tube has very rugged electrodes and is rated at 24,000 watt-seconds (joules) per flash maximum.

Some measurements were made on two smaller tubes having helical configurations, the FT-403 (Pyrex) and the FT-524 (quartz, and same as FT-503). The FT-524 is rated at 2,000 joules, but can be operated at 3,200 joules for nonrepetitive use. However, it was necessary to remove these types from their bases to mount them in the pyrolyzing unit.

CIRCUITRY

Energy is supplied to the flashtube from a portable capacitor bank containing four 100 μ f (approximate value) capacitors rated at 4 KV and mounted so that any number of them can be readily connected in parallel. The capacitors are charged through a limiting resistor by a small, high-voltage power supply which has a d.c. output continuously variable from zero to 5 KV, and the voltages across the capacitors were read from a calibrated voltmeter to within 20 volts (see Fig. 2). The thyatron circuit which energizes the primary of the trigger transformer is included in the power supply unit.

The actual value of each capacitor was checked by an a.c. capacitor bridge and then calibrated by carefully measuring the RC time constant of a discharge circuit comprised of precision resistors connected across the capacitor.

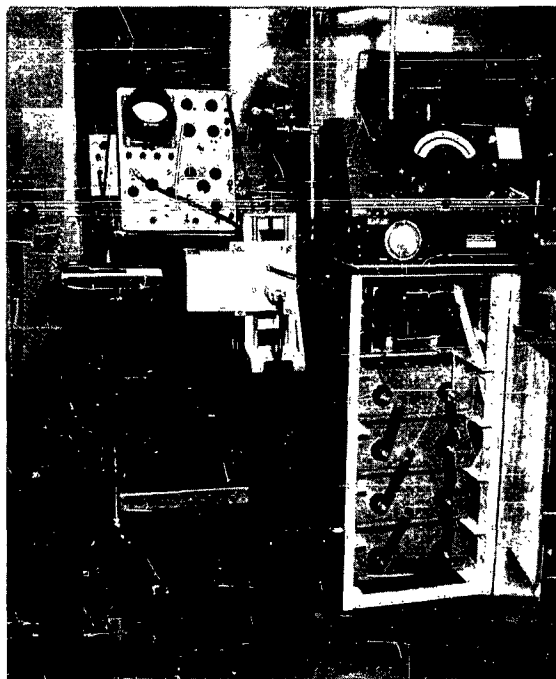


Fig. 2. Assemblage of most of the experimental equipment showing the 5 KV power supply sitting atop the 400 μ f capacitor bank. The photodetecting unit is shown above the pyrolyzing chamber which is secured to its carriage.

EFFECT OF CIRCUIT INDUCTANCE

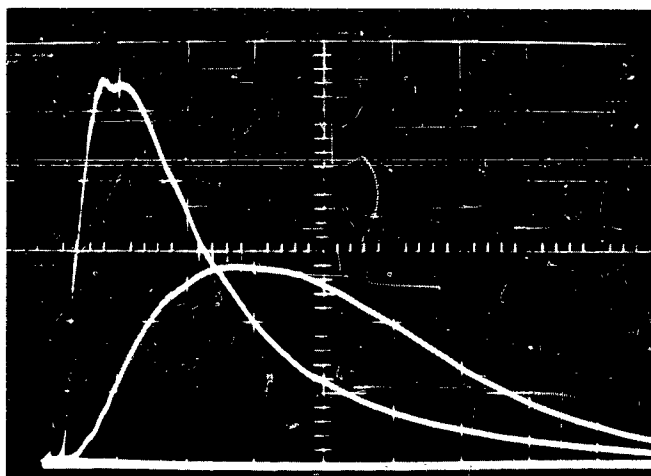
The influence on the shape of the light pulse due to a series inductance added to the circuit is illustrated graphically in Fig. 3. The two curves result from identical parameters except for the insertion of a 0.6 millihenry choke in series between the capacitor and the flashtube; it is evident that the added inductance reduces the peak amplitude but increases the pulse duration both electrically and optically. However, the total energy radiated by the flashtube is not significantly reduced, if the resistance of the choke is negligible compared to that of the flashtube. In the circuit associated with Fig. 3, the ohmic resistance of the choke was 0.5 ohm and not negligible compared to the 3 ohms of the flashtube. According to Marshak and Shchoukin,³³ circuit inductance less than 100 μ h does not significantly influence the light output from tubular flashtubes, but at 2500 μ h the pulse duration is doubled and the total output is decreased by 30%.

Inasmuch as the present work requires short-duration, high-energy pulses, circuit inductance has been kept to a minimum and the data reported herein result with no choke in the circuit.

MEASUREMENTS

Because the primary interest in this work has been confined to the thermal performance of selected available flashtubes, no measurements on the effects of varying tubing length or diameter, gas pressure, voltage gradient, etc. have been included. Extensive studies on these aspects of flashtube technology have been undertaken by other investigators.^{11,20,33}

(1) Current and Voltage. The discharge current through the flashtubes was measured by applying to an oscilloscope the voltage drop across a .001 ohm meter shunt in series between the capacitor bank and the flashtube.



200 μ sec/division

Fig. 3. Oscillogram showing the effect of a series 0.6 mh choke on the light output from a FT-625 discharge of 290 μ f at 4.0 KV. Upper: no choke in ckt. Lower: identical discharge with the choke in the ckt. Vertical units are the same for both curves.

Similarly, the instantaneous voltage across the flashtubes was measured by connecting a resistive voltage divider across the tube to reduce the voltage fed to the oscilloscope by a factor of 500. The combination of a dual trace oscilloscope and a camera made possible the simultaneous recording of flashtube voltage and current as a function of time for single flashes.

In addition, oscillograms showing light output as a function of flashtube current were obtained by applying the voltage from a phototube circuit to the vertical amplifier and the voltage resulting from the flashtube current to the horizontal amplifier of the oscilloscope.

(2) Thermal Irradiance. The chief interest was measurement of the thermal radiation received by cellulose samples when placed in the center of the helical flashtubes. A simple, yet accurate calorimeter for measuring this thermal energy was constructed from a 1.28-cm segment of .97-cm O.D. hollow, pure silver cylinder with a wall thickness approximately 1.0 mm and a total weight of 3.598 gm. Two holes were drilled parallel and diametrically opposite to one another in one end of the cylinder, and a chromel wire was peened into one hole and an alumel wire into the other to complete the thermocouple circuit through the element itself. The outer surface only of the cylinder was platinum blackened by deposition from chloroplatinic acid solution. As shown in Fig. 1, the cylinder was suspended vertically by the thermocouple wires and enclosed within a Pyrex jacket which was connected to a vacuum system and continuously pumped during irradiations. The temperature increment of the calorimeter element resulting from each flash was measured by connecting the thermocouple leads directly to a Brown-type potentiometric recorder.

Although the recorder could not follow the temperature increase, a good cooling curve of the calorimeter element was obtained for each flash, and this was extrapolated back to the instant of the flash to give the total temperature increment. Because of the evacuated jacket,

the slope of the cooling curves was quite gradual and lent greater precision to the extrapolations. For the most part, this technique yielded reasonably good precision in that discharges resulting from the same settings of voltage and capacity produced temperature increments reproducible usually within one per cent. The energy absorbed per square centimeter by the calorimeter from each flash was then calculated from the temperature rise, the known weight of the silver cylinder, its heat capacity, and its surface area. The absorptance of the Pt black was assumed to be unity. Renewal of the black was necessary when after about a dozen exposures, the black tended to become slightly gray. With this experimental technique, it was possible to measure cal/cm^2 per flash inside of the helix for numerous combinations of voltage and capacitance.

(3) Spectral Considerations. Narrow-band interference filters combined with vacuum phototubes PT-935 and PT-917 were used in conjunction with a dual trace scope equipped with a camera to record simultaneously light intensities at 0.35 and 1.01 microns as a function of time; this also made it possible to observe any sequential difference in the short and long wave length portions of the light pulses.

DETERMINATION OF IRRADIANCE

Ideally, the radiant power as a function of time would be measured using a receiver whose spectral response is flat from 0.3 to 4 micron, and whose time constant (including leads) is less than 10 μsec . Unfortunately, black-body radiometers are not that fast. Therefore, to establish the time-irradiance characteristics of the flashtubes it is necessary for each flash to record the light pulse using a photosensitive device whose output is proportional to the irradiance and then equate the area under this light-time curve to the radiant energy measured simultaneously by the black-body calorimeter.

In choosing photosensitive detectors to record the shape of the total radiant pulse from each discharge, the two major factors of concern are spectral response and time response. In general, vacuum phototubes (or multipliers) in circuits having low load resistance are adequately fast, but have poor response in the infrared. Of the possible phototubes, it was concluded that only those with an S-1 response (such as the PT-917) give a reasonably close intensity-time representation of the total thermal pulse. On the other hand, most of the photoconductors have adequate infrared response, but are much too slow. Fortunately, one of the lead selenide photoconductors on hand exhibited an adequately short time response for this work. Also, the PbSe response was assumed to be closer to that of a black-body because its response extends from below the blue to beyond the infrared limit of the Pyrex transmission, despite the fact that it is not flat over this range and tends to exaggerate the longer wave length intensities. Light measurements for the peak irradiance calibrations described herein were made by operating the PbSe photoconductor with a series load of 10 kilohm across 45 volts within the linear range of illumination vs. current; the output voltage was presented on a Tektronix type 533 oscilloscope and photographed with a Polaroid Camera.

The total area recorded on each oscillogram was doubled by presenting for each flash two sweeps of the scope on one photograph. This was accomplished by simultaneously triggering the flashtube, the scope, and a time-delay circuit. The delay circuit triggered a second sweep on the scope immediately after the first, and thus more of the tail of the light pulse was recorded; this permitted greater accuracy in graphical integration of areas under the curves directly from the oscillograms by the use of a planimeter. Fig. 4 is an example of one such oscillogram. These areas were determined in units of the divisions on the oscillograms and equated to the total energy per square centimeter received by the calorimeter during the same flash. From this

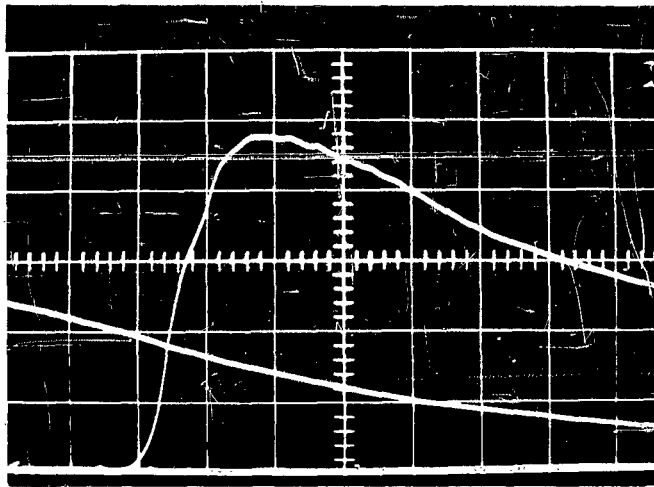


Fig. 4. Typical single-trace double-sweep oscillogram of a photodetector signal vs. time ($50 \mu\text{sec/cm}$). This is the light output from a FT-625 discharge of $193 \mu\text{f}$ at 3.0 KV .

the irradiance level per vertical division on each oscillogram was calculated and the irradiance in $\text{cal}\cdot\text{cm}^{-2}\text{sec}^{-1}$ at any point of time during the flash could be readily determined.

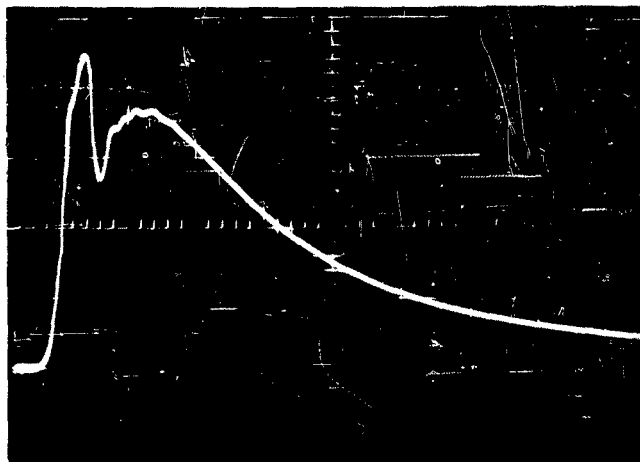
The order in which identical discharges were repeated for data acquisition was randomized to avoid systematic errors due to such causes as loss in calorimeter or photodetector sensitivity. Moreover, each flash was monitored to verify the reproducibility of the pulse shape obtained from a given combination of capacitance and voltage.

RESULTS AND DISCUSSION

ELECTRICAL CHARACTERISTICS

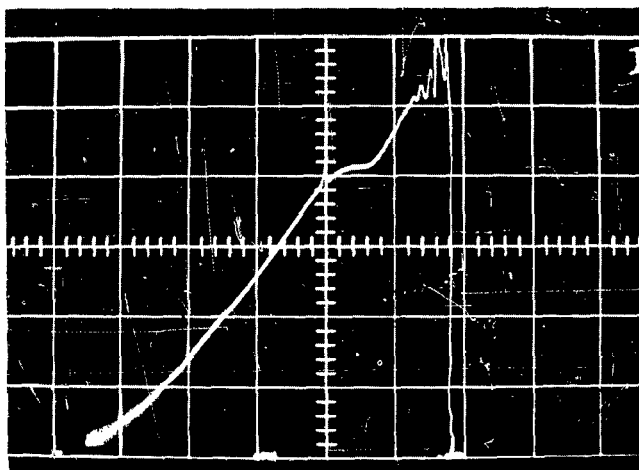
In low inductance circuits, the oscilloscopic traces of current vs. time for the three types of flashtubes show a sharp initial current or spike which is usually 20 to 80 per cent greater in amplitude than the main peak. (See Fig. 5.) This spike is the initial cycle of a highly damped oscillation always present in the early portion of the current pulse; the oscillation is of the order of magnitude of 50 kilocycles and varies with capacitance.

Oscillograms displaying simultaneously the flashtube voltage and current vs. time show that the resistance of the tubes varies somewhat during discharge, because the current always manifests a faster rate of decay than the voltage. This non-ohmic relationship is displayed more clearly in Fig. 6 which presents current as a function of voltage. At the beginning of the pulse, the resistance is near a minimum and increases slightly during the discharge. This is in fair agreement with Carlson.¹⁴ Measurements from a number of current-voltage oscillograms show that the average resistance of a FT-625 is nearly independent of the capacity and voltage and is approximately 2.7 to 3.2 ohms.



50 $\mu\text{sec}/\text{cm}$

Fig. 5. Typical flashtube current pulse. Discharge of 97 μf at 5.0 KV through a FT-625.



500 volts/cm

Fig. 6. The relationship between current and voltage during a typical discharge of a FT-625. Input is from 386 μf at 3.0 KV. (In this case the trace terminated after about 2000 μsec and before it returned to the origin as it progressed from right to left.)

However, a more significant quantity is the dynamic resistance, i.e., the slope of that part of the current-voltage curve which corresponds to the major portion of the decay. This is about 1.8 to 2.2 ohms for the FT-625. For any of these discharges, a plot of the logarithm of the instantaneous current vs. time yields a straight line over most of the tail, thus showing that at least part of the current flow has an exponential decay. Moreover, the measured time constant, t , of this exponential decay agrees with the value calculated from $t = RC$ where R is the dynamic resistance of the flashtube. The resistance values of the FT-524 evidence somewhat greater variation with circuit parameters. The average resistance usually falls within 3.5 to 4.5 ohms, and the dynamic resistance is approximately 2 to 3 ohms.

RADIANT EMISSION

Although the behavior of electric discharges within the flashtubes is of considerable complexity,^{7,10,11,15,30,33} it is clear that the observed light emissions for a given tube are controlled by the electrical parameters of the external circuit.^{7,9,13,14,17,23,24,28,31,33} The shape, duration, and intensity of the light pulse depends on several factors including (1) type and shape of flashtube, (2) total capacitance, (3) voltage to which capacitors are charged, (4) inductance and resistance in the discharge circuit, and (5) per cent of circuit energy expended in the flashtube. Factors other than circuitry, such as reflectors and location of specimen with respect to the flashtube, also have significance.

Information in the literature on the spectral distribution of the light emitted by the discharge of flashtubes is meager. Nevertheless, it is realized that the spectral distribution is a function, primarily, of the current density which, in turn, is dependent on the voltage across any given tube. Olsen and Huxford¹⁷ have suggested that the

densely ionized plasma radiates as a "gray body" and exhibits a spectral maximum which is temperature dependent. Various investigators^{10, 14, 15, 16, 18, 19, 30} report information within limited portions of the spectrum showing that the xenon discharge light is essentially white and continuous in the visible region; however, at low current densities or low gas pressures (below about 40 mm Hg), the continuum is replaced by the xenon line spectrum.²¹ Barstow¹⁹ has pointed out that there is adequate IR from the flashtube discharge to make it a source for the near IR. One of the best references on spectral distribution is the General Electric Flashtube Manual.²⁸ These sources agree that the major spectral peak is around 4500 Å and a broad minor peak lies between 8000 to 10,000 Å with only a shallow dip between them. The relative heights of the two peaks is contingent upon the initial discharge voltage for any given flashtube. At the comparatively high voltages, the shorter wave-length peak predominates, but near the minimum operating voltage the longer wave-length peak is nearly equal in intensity. This effect is shown in Fig. 7, although here the dominance of the blue region is somewhat reduced because the intensity at 3500 Å is less than at the 4500 Å peak. Radiations from xenon discharges are often compared to those of black-body radiators at temperatures of 6000 to 7000°K;^{14, 15, 16} however, such consideration is usually valid only for the visible part of the spectrum.

This effect of voltage on the spectral distribution shows up in the field calorimeter experiments which determined the amount of energy at wave lengths longer than 1.0 micron. (See Table I.) Because the transmission characteristics of the Corning No. 7-56 filter extend to nearly 2.8 micron, it is reasonable to assume that these values represent a good approximation to the total energy radiated by a quartz flashtube beyond 1.0 micron.

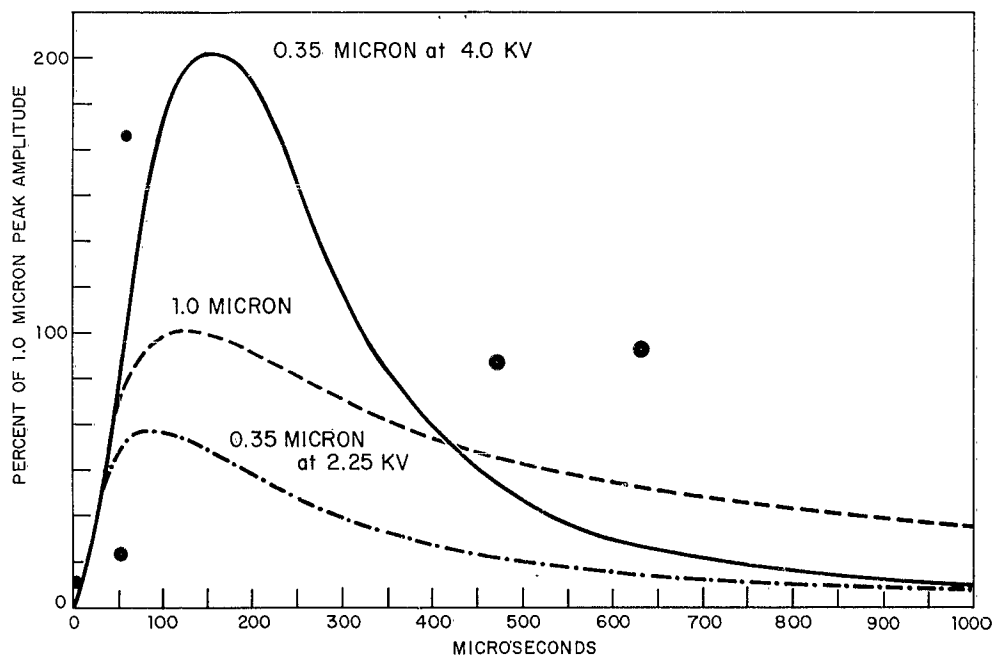


Fig. 7. A comparison showing the effect of voltage on the relative amplitudes of wave lengths in the ultraviolet and infrared parts of the emission from a FT-625 with a 290 μ f capacitance. The relative amplitudes are adjusted so that the 1.0 micron curve is the same for both sets of conditions.

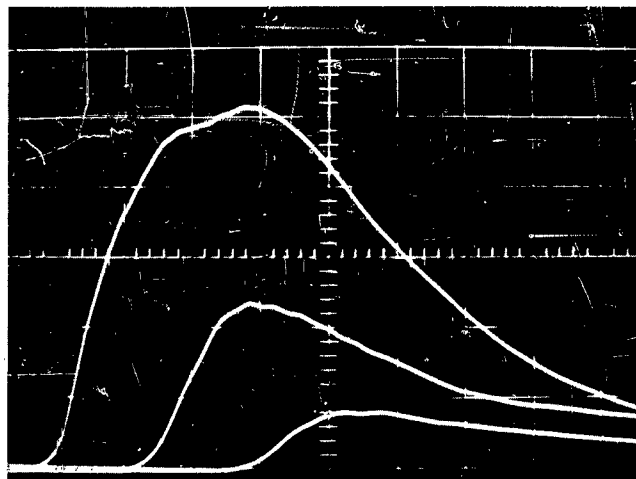
TABLE I

PER CENT OF FT-625 EMISSION AT WAVE LENGTHS LONGER THAN 1.0μ

<u>Voltage</u>	<u>Capacitance</u>	<u>Joules</u>	<u>% $> 1.0\mu$</u>
5.0 KV	97 μ f	1200	19
2.2	386	880	25
3.0	386	1730	22

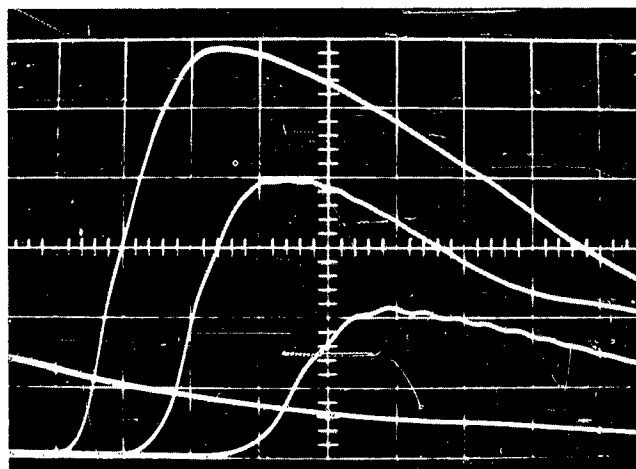
The effect of voltage variation on the radiant output at opposite ends of the spectrum is further demonstrated in Fig. 8. Along with Fig. 7, it may also be noted that the shapes of the curves at the two wave lengths are different. The short wave lengths normally reach maximum intensity slightly sooner, but it is evident that they drop off much faster and are, therefore, shorter in duration. This fact is also in evidence in the oscillograms showing light output as a function of current with no choke in the circuit. (See Fig. 9.)

Here it can be seen that the current reaches its maximum value before any appreciable light is emitted, then the light goes to a maximum while the current is near maximum and then decays with the current (the ripples are due to current oscillation at the peak). Hoyt and McCormick¹⁸ have observed that for most flashtubes filled with noble gases, the light intensity is approximately proportional to current. However, the data from this work has shown that the radiant intensity is not directly proportional to current during the flash. Actually the exponential decay portion of the light curves differs from the corresponding part of the current curves in that the time constant for the light (corresponding to the PbSe spectral response) is approximately equal to $RC/1.4$ while that for the current is equal to RC (where R is the dynamic resistance). Cloupeau³⁰ has



50 $\mu\text{sec}/\text{cm}$

(a) Intensity at .35 micron

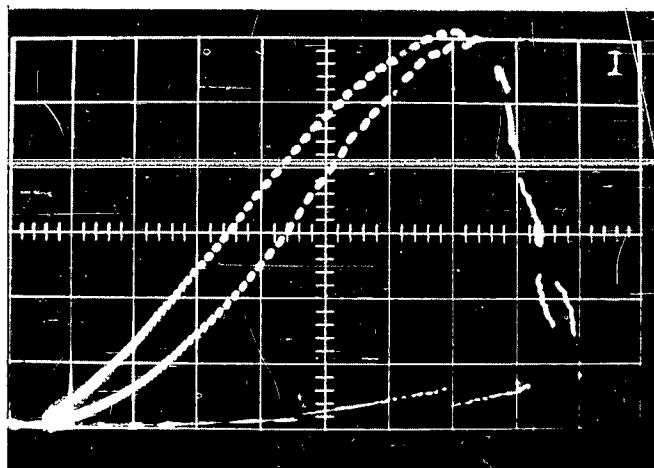


50 $\mu\text{sec}/\text{cm}$

(b) Intensity at 1.0 micron

Fig. 8. Oscillograms showing the effect of voltage variation on the radiant intensity at the UV and IR ends of the spectrum [vertical units are not the same for (a) and (b)]. The FT-625 with a circuit capacity of $193 \mu\text{f}$ was discharged at 4.0, 3.0, and 2.2 KV. It is also apparent that the delay between triggering pulse (of constant magnitude) and the flashtube discharge varies inversely with the capacitor voltage.

Light Intensity in Arbitrary Units



Current

Upper sweep: 1.0 micron
Lower sweep: 0.35 micron

Fig. 9. Simultaneous display of the light output at two wave lengths for a single discharge of a FT-403 at 2.0 KV and 96 μ f. The intensities at .35 and 1.0 micron were adjusted at the detectors to yield equal amplitudes at their peaks. The time sequence of the trace begins at the lower left corner and proceeds counter-clockwise.

reported that the light (except in the blue region) continues after the end of the electric discharge, but this was not observed in the comparatively long time-duration discharges reported here.

Edgerton, Bonazoli, and Lamb⁹ have defined flash duration as the time lapse between the one-third points of the peak light pulse, and this has become a widely accepted standard. However, this work has revealed that pulse width, τ , defined as the time lapse between the $1/e$ points of the peak is more useful, because the product of the peak height and τ is equal to the area under the curve to within 5%. The dependence of τ on the voltage and capacitance is exhibited in Figs. 10a and 10b wherein each point represents an average determined from several oscillograms displaying the signal from the PbSe photo-detector vs. time. From these graphs, it is evident that the circuit capacitance has predominant influence on the flash duration, and above approximately 800 joules τ varies linearly with the capacitance.

CORRELATION BETWEEN ELECTRICAL INPUT AND THERMAL OUTPUT

Two attractive features of employing flashtubes as sources of thermal radiation are (1) the good reproducibility obtained from flash to flash by duplicating the external electrical parameters V and C and (2) the ease of adjusting the shape, magnitude, and duration of thermal pulses by simple variation of these same parameters, both of which are easy to measure. The range over which these thermal pulses can be varied is dictated, primarily, by the electrical operating limits for each type of flashtube.

The relationship between the radiant energy incident at the axis of the helical flashtube and the electrical energy dissipated in the flashtube is shown in Fig. 11 where each point represents an average of several flashes. The 4.5 and 5.0 KV points are somewhat low presumably because at the higher voltages a larger per cent of the

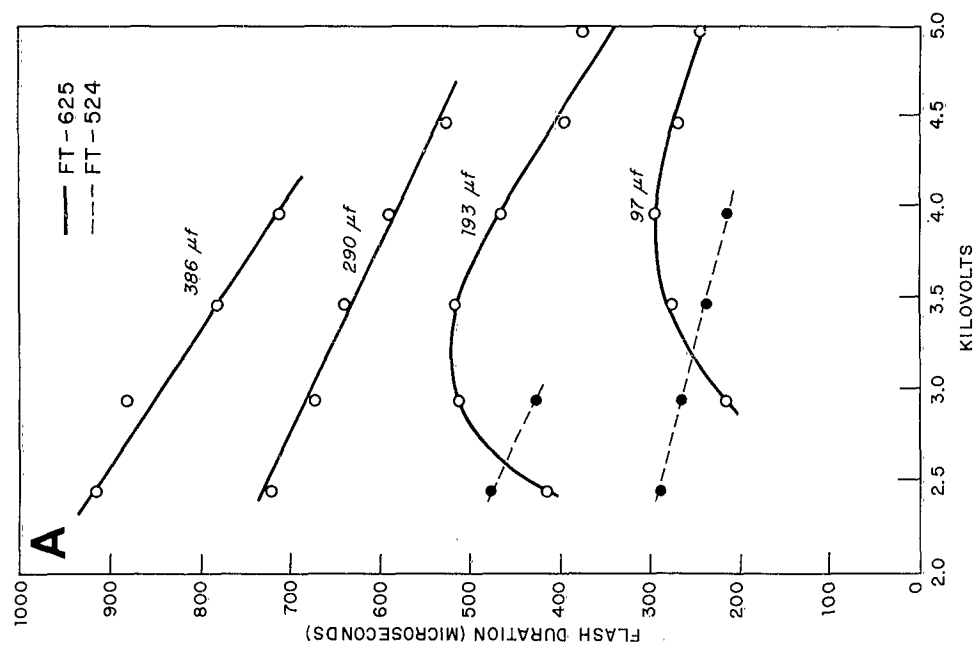


Fig. 10a. The influence of capacitance and initial voltage on the light duration (the time between 1/e points of peak intensity) of flashtube discharges.

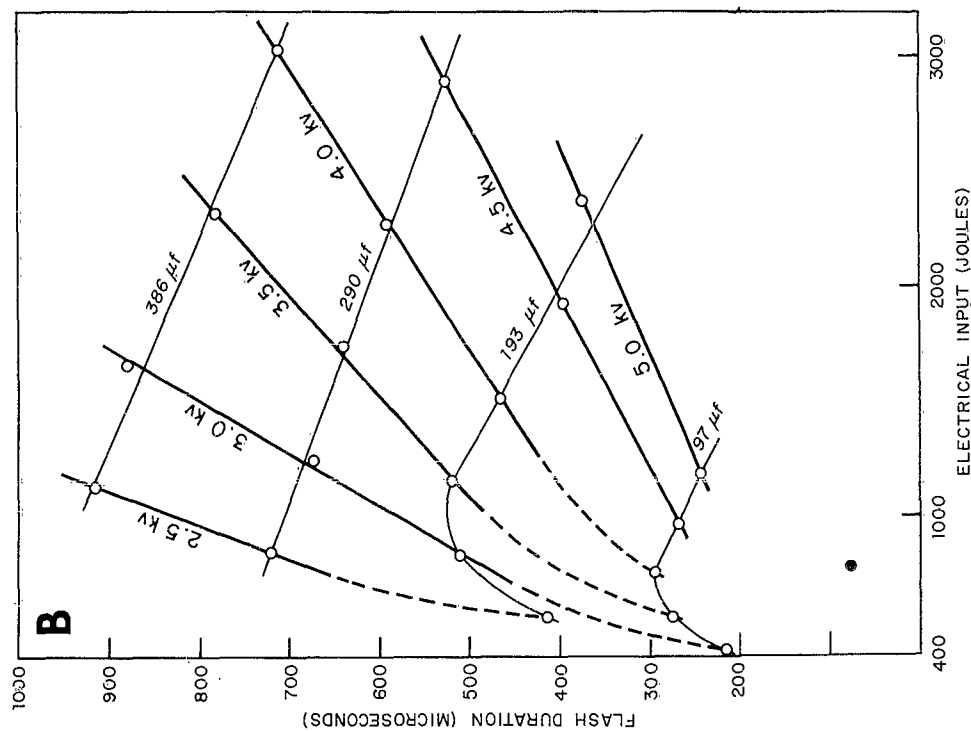


Fig. 10b. The influence of external circuit parameters on the duration of light pulses from the FT-625 flashtube.

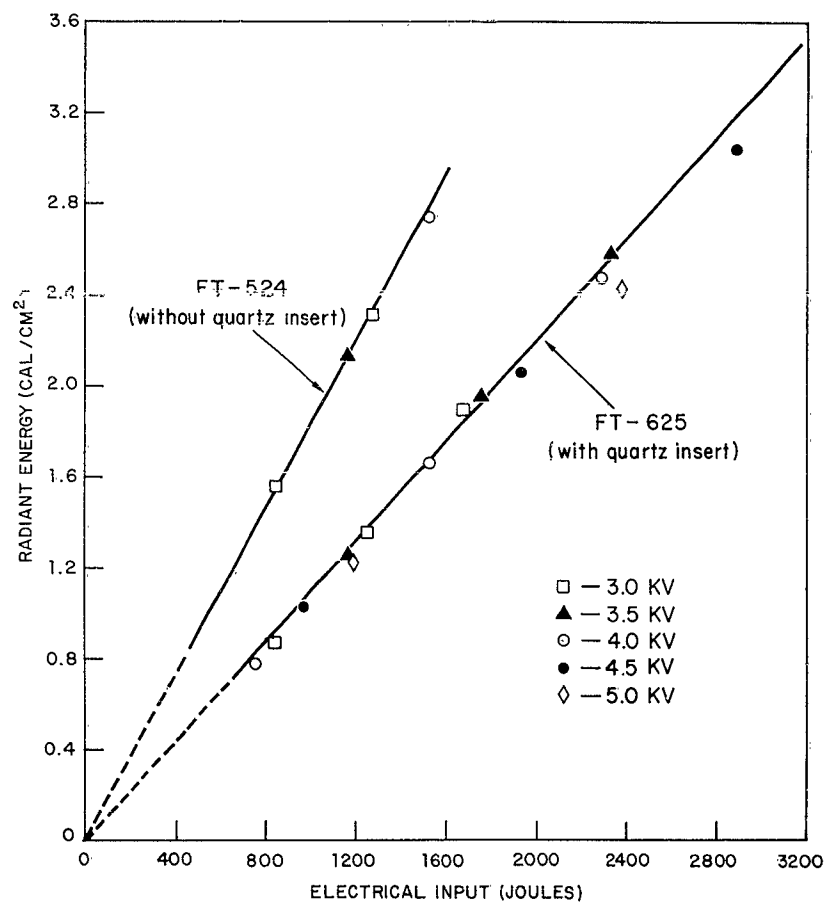


Fig. 11. Radiant energy for each flash as a function of electrical input energy

radiant energy is in that part of the short wave-length region not transmitted by the Pyrex calorimeter envelope.

The electrical input shown here is only that energy expended in the circuit:

$$E = \frac{C}{2} \cdot (V_i^2 - V_f^2). \quad (1)$$

E is in joules when the voltages are expressed in kilovolts and the capacitance in microfarads. V_i is the initial voltage across the capacitance and V_f the residual voltage after discharge.* This relationship holds for the flashtube itself only if the ohmic losses in the external circuit are negligible. The presence of an inductive component will not alter the relationships shown in Fig. 11, but because the resistance of a large flashtube is only about three ohms, a choke with even a small resistance will introduce significant losses and will reduce the radiant output, thereby decreasing the slope of the line in Fig. 11. It is evident from this plot that

$$Q = kE \quad (2)$$

where Q is the total radiant energy per square centimeter per flash along the interior axis of the flashtube, and from this it is clear that Q is directly proportional to both voltage squared and capacitance. Another significant fact here is that with each type of flashtube, k has the same value for all combinations of voltage and capacitance, i.e., the radiation efficiency is constant over the ranges of C and V employed. From Table II, it is apparent that the FT-625 on a per unit area basis is not the most efficient of the flashtubes, but its chief advantage is its greater energy handling capability.

* The extinction voltage is about 200 volts for the large flashtubes.

TABLE II

VALUES OF k RELATING FLASHTUBE RADIANT
ENERGY TO ELECTRICAL INPUT ENERGY

<u>G. E. Flashtube</u>	$\frac{k}{\text{cal}\cdot\text{cm}^{-2} \text{ joule}^{-1}}$
FT-625	1.10×10^{-3}
FT-503	1.71×10^{-3}
FT-403	1.4×10^{-3}

The reduction in irradiance due to the Pyrex jacket and the quartz insert was also measured. It was found that for 3-KV discharges with no insert present, the k values should be increased 7.0 per cent, and without the Pyrex tubing, an additional 7.5 per cent should be added. This is in close agreement with the typical value of 8 per cent reflective loss through two surfaces. These same increases should be added to peak irradiances under similar conditions. Applying these corrections to the FT-625 will give $k = 1.27 \times 10^{-3} \text{ cal}\cdot\text{cm}^{-2} \text{ joule}^{-1}$ which is a little higher than the 1.0×10^{-3} value obtained from the graph of Kuebler and Nelson²⁷ for discharges with their low inductance capacitor bank and a similar flashtube; however, most of this discrepancy can be attributed to a difference in reflectors. Their second and much lower value of k resulting from a circuit which included a choke indicates that the choke probably had significant resistance.

PEAK IRRADIANCES

The peak irradiances obtained from the FT-625 (no choke in circuit) in conjunction with various combinations of electrical parameters are presented in Fig. 12. As might be expected, the voltage is the most influential factor on this particular property, and it is a linear function of the voltage squared and tends to be independent

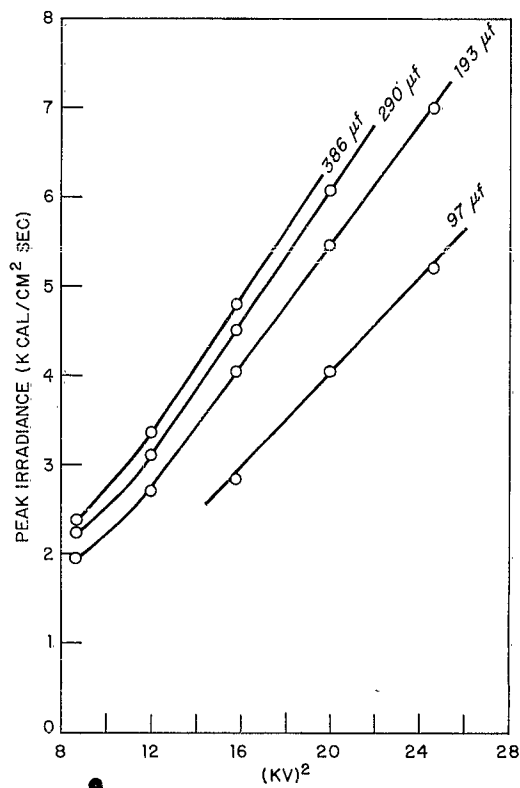


Fig. 12. Influence of electrical parameters on the peak irradiance from an FT-625

of capacitance at the higher values of capacitance.

Although all the values for Fig. 12 were obtained by integrating the light pulses as previously described, it was found that the relationship

$$H_p = \frac{Q}{\tau} \quad (3)$$

gives results which are very close to these values yet much more readily obtained. Moreover, by substituting equations (1) and (2) into (3), a very good approximation to the peak irradiance can be easily calculated:

$$H_p = \frac{kC}{2\tau} \cdot (V_i^2 - V_f^2) \quad (4)$$

Here the last term may be neglected and the resulting simplified expression is

$$H_p = \frac{kC}{2\tau} \cdot V_i^2$$

TEMPERATURE

Nelson and Lundberg³ have calculated some temperature rises of flash-irradiated finely divided materials and have shown that the optimum size for rod-shaped objects is approximately 10 microns in diameter. Experimentally, they were able to evaporate tungsten wire explosively at 5184 joules. Within this project, the technological obstacles to the measurement of high temperatures over very short times have deterred attempts to actually measure the temperatures attained in irradiated materials. Nevertheless, included in this work have been some approximate determinations of attainable temperatures by utilizing the melting points of several metals. With input energies of about 1500 joules into the FT-625, single discharges melted fine copper mesh (1083°C), nickel mesh (1452°C), and 0.5 mil blackened platinum wire (1755°C). Additional experiments have demonstrated that the energy required to melt one-mil, platinum-blackened

copper foil is 1700 joules which corresponds to slightly less than 2.0 cal/cm^2 radiant energy. Thus, the absorbed energy required to melt the copper foil is 3.9 cal/cm^2 , and this is a reasonable correlation with the value of 3.7 cal/cm^2 calculated from the specific heat and heat of fusion.

Since these temperatures were obtained using only comparatively low energies and irradiances, it is clear that the heating of solid materials to considerably higher temperatures is well within the realm of possibility with this same equipment.

ERRORS

To check for possible errors resulting from either electrical pick-up or inductive heating of the calorimeter, an opaque dielectric cylinder was placed around the calorimeter which was within the flash-tube in its normal position. Discharges of 1730 joules each produced no perceptible voltage from the calorimeter thermocouple.

One source of error which must be considered is the extrapolation of cooling curves to determine the temperature increment of the calorimeter element for each flash. However, this was not a serious problem with the vacuum calorimeter, because the silver cylinder equilibrated thermally in 4 seconds and the subsequent rate of cooling normally was approximately 2% per second. The typical standard deviation on a series of extrapolated temperature increments was a $\pm .4\%$. The absorptivity of the Pt black surface of the Ag calorimeter element was assumed to be 1.00. The reflectance of Pt black on silver has been studied previously³² and found to be constant at slightly less than 2% from 0.25 to 2.5μ ; however, there is a slight absorption by some of the unblackened portions of the Ag cylinder which are exposed to the radiant flux, and this small contribution was regarded as making an equivalent net absorptance of close to unity for the

blackened surface. Losses due to black body radiation were considered to be negligible, because the temperature increments were less than 60°C . Thus, the accuracies for the values of Q are judged to be within $\pm 3\%$ at least for a specific flashtube.

Values given for peak irradiances suffer inherently from errors of much greater magnitude than those for total irradiance per flash. In addition to the errors already mentioned, the graphical determination of the area under the time-intensity curves is the least accurate. Moreover, the proximity of the photodetector response to a black-body receiver is a factor in describing the shape of this curve and the consequent rate at which the energy is delivered. Thus, the values of irradiance are considered to be accurate only within $\pm 5\text{-}10\%$.

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<p>of intensity vs. time. Thermal pulses were found to be quite reproducible and are of the order of 1.0 to 1.7 cal/cm² per thousand joules of electrical input energy depending on the type of flashtube. Peak irradiances of over 7,000 cal·cm⁻²·sec⁻¹ were observed, and the influence of varying the capacitance and voltage was also determined.</p> <p>In addition, some electrical characteristics of the flashtubes, such as current and resistance were included in the measurements.</p> <p>UNCLASSIFIED</p>	<p>1. Flash lamps. 2. Thermal radiation, 3. Pyrolysis. 4. Cellulose.</p> <p>I. Lincoln, K.A. II. Title.</p> <p>UNCLASSIFIED</p>